# 29th International Symposium on Ballistics

# Injury Characterization Due to Penetrating Projectiles

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# Background

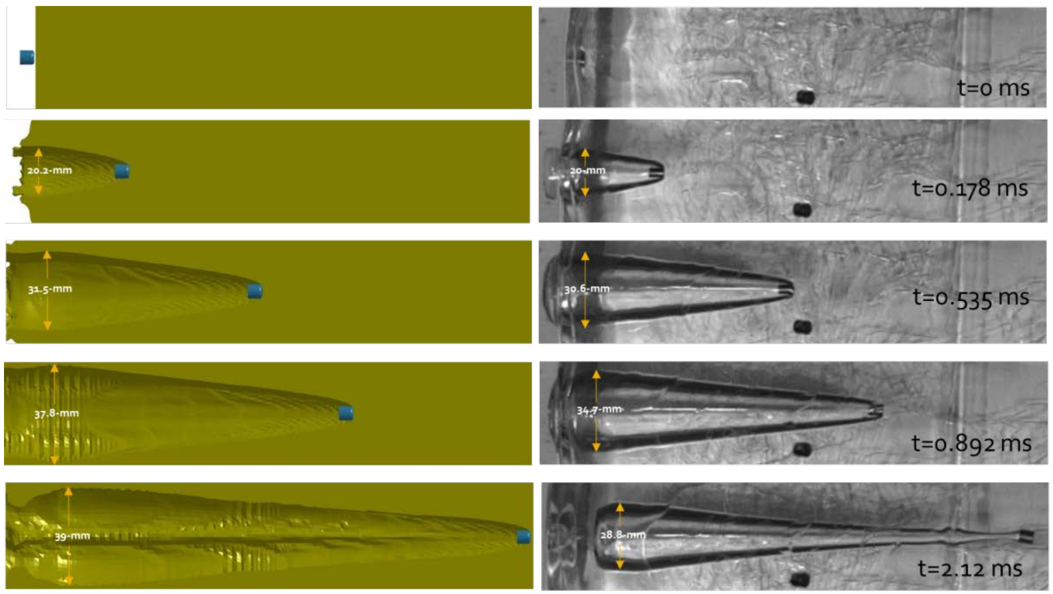
- The US Office of Naval Research (ONR) is developing simulation tools (fast-running models) for armor ballistic performance and penetrating injury response
- These new models use Monte-Carlo based probabilistic methods to account for the inherently statistical nature of threat engagement with PPE armor solutions and penetrating injury dynamics
- CPAT – Comparative Protection Analysis Tool – is a design tool for comparison, optimization and trade-off evaluations for PPE, specifically ceramic/composite and composite or soft armor solutions
- NAVSAM – Navy Survivability Assessment Model – is an extension of CPAT in which penetrating injury to the human body due to projectiles that perforate the PPE armor are modeled

# Background

- A critical element to the evolving predictive capabilities of CPAT and NAVSAM is improved model forms that account for the complex interactions between the threat, armor, and human body
- These improved models require validation data from appropriate experiments to insure accurate and realistic simulation results, as well as providing new physical insights based on the data
- Thus, the objective of this effort was to develop an experimental methodology for measuring pressure and strain in soft tissue simulants during ballistic impact and penetration
- The soft tissue simulant was Perma-gel
- The threat projectiles were Fragment Simulating Projectiles (FSP) – 2, 4, 16, and 64 grain steel RCC; and bullet projectiles – 0.22-cal Long Rifle (LR) 40 grain and 7.62X39 PS 123 grain
- The data collected in this effort can be used to validate both fast running penetrating injury models and high resolution Finite Element models

# Wound Characteristics

LS-DYNA Simulation | Experimental Data




Temporary wound cavity formation – “stretch”

Permanent wound cavity - crush

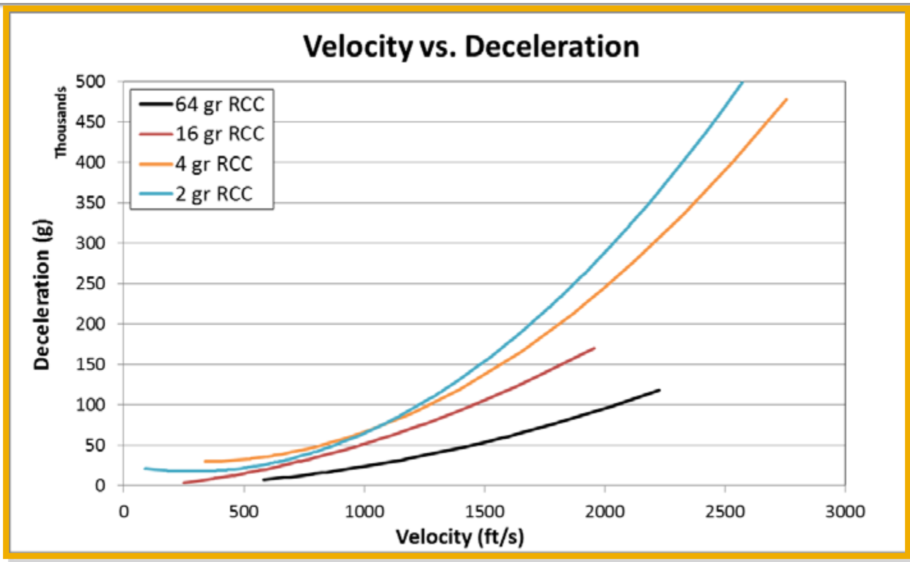
Five variables are key to understanding ballistic wounds and projectile-tissue interactions: projectile mass, projectile shape, projectile construction (material distribution), projectile striking velocity, and target tissue type

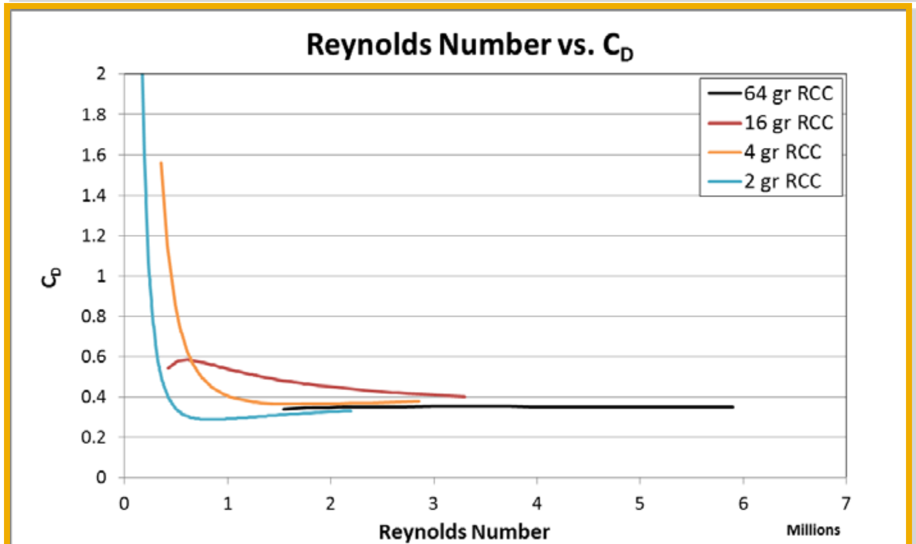
# Wound Characteristics

- ***Potential*** for tissue damage is characterized by projectile mass and striking velocity.
- ***Actual*** damage (volume, type, and location) depends on projectile shape, projectile construction, and tissue type (connective, muscle, organ, vascular, or bone)
- Ballistic wounding is a highly dynamic event in which projectile drag during tissue penetration results in energy loss, which equals the work done on the tissue
- Projectile *retarding force* – force that the tissue applies to the projectile during penetration – characterized by the projectile drag coefficient (viscous and pressure drag)
- Regardless of impact energy, if the *retarding force* is comparable for a given projectile trajectory, then the wound magnitude will also be comparable

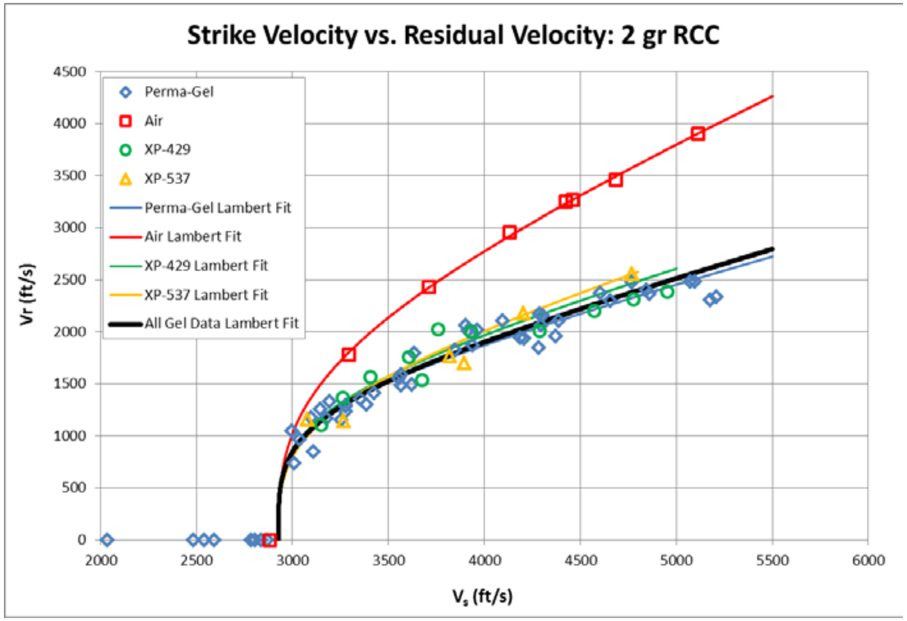
# FSP (RCC) Penetration Summary

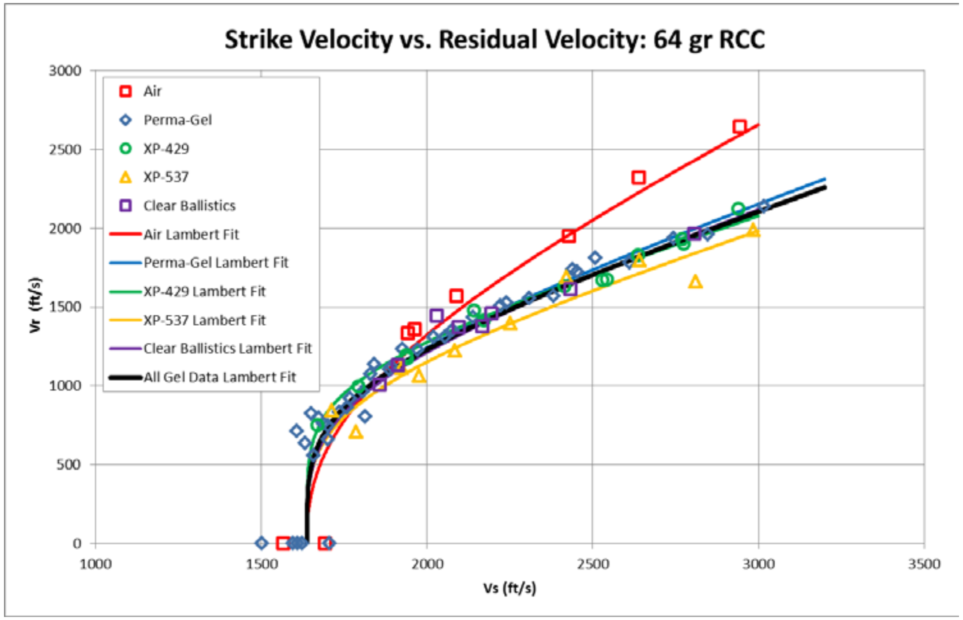
- Projectile drag coefficient and thus the retarding force is a function of projectile projected area and the speed of impact – shown here are measured data for deceleration and drag coefficient ($C_D$) for the FSP projectiles in Perma-gel
- Due to the higher energy and momentum of the shot 64 gr RCCs, it appears that the flow field around the projectile stays in the turbulent flow regime and thus achieves a constant coefficient of drag for all entrance or strike velocities tested
- The lighter 16 gr RCC decelerates more per given velocity and begins transitioning flow regimes as it slows down from turbulent to laminar. This results in a $C_D$ that is no longer constant through its trajectory
- The 4 gr and 2 gr RCC's decelerate significantly per given velocity and appear to transition into a laminar flow regime with large $C_D$ gradients between high and low velocities
- At high Re's (or strike velocities), all the projectiles converge to a constant $C_D$ of **0.35**, which confirms or validates this analysis methodology



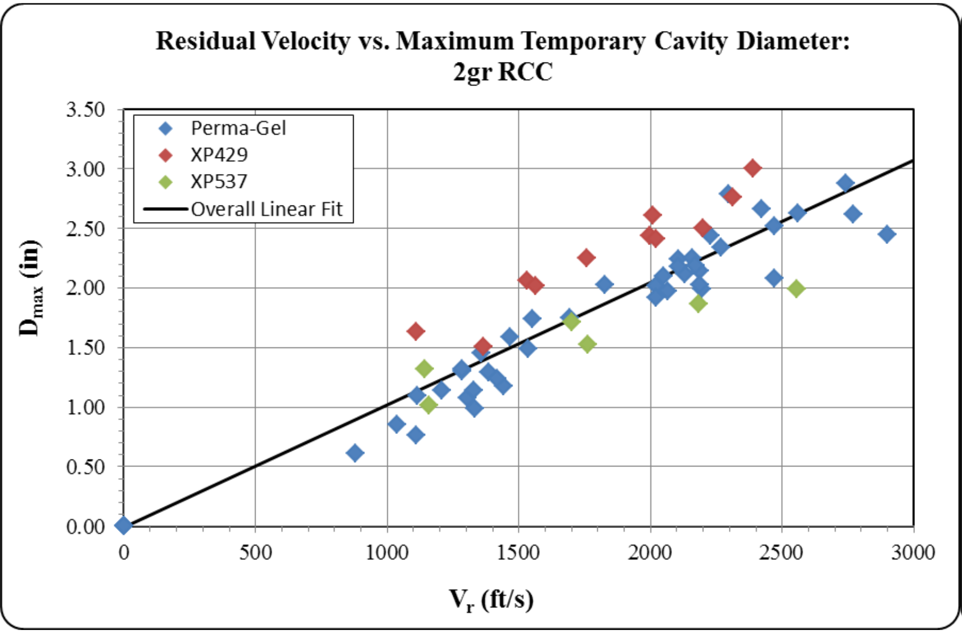
# FSP Wound Characteristics – Residual Velocity

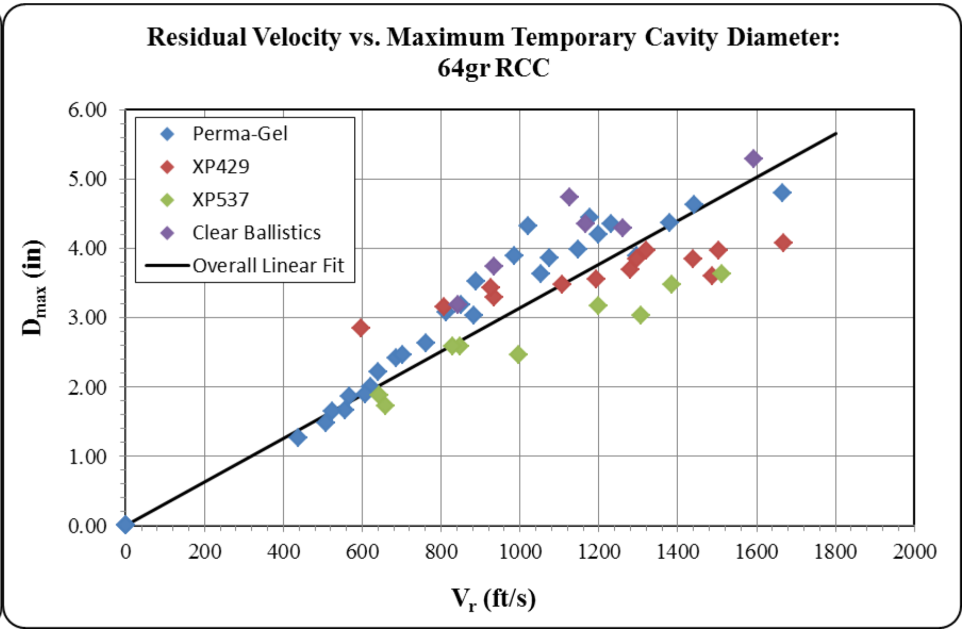



Experimental data of residual velocity for 2-gr and 64-gr FSPs penetrating different simulants for human tissue – dynamic response is similar for all simulants – data is extracted from digital high speed video data

# FSP Wound Characteristics – Temporary Wound Cavity Diameter

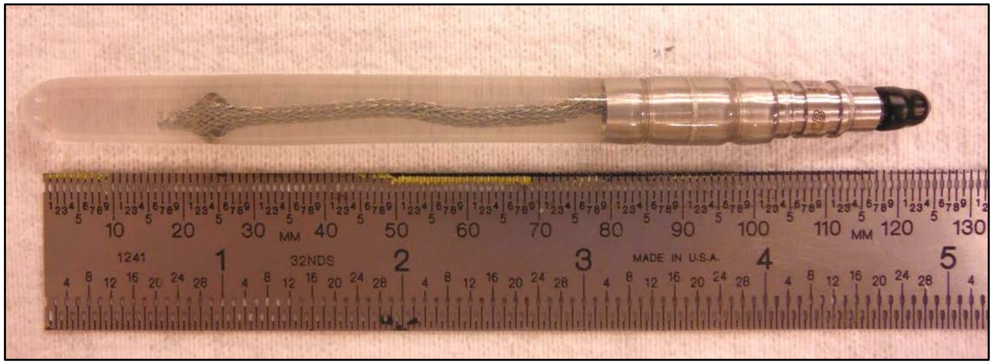


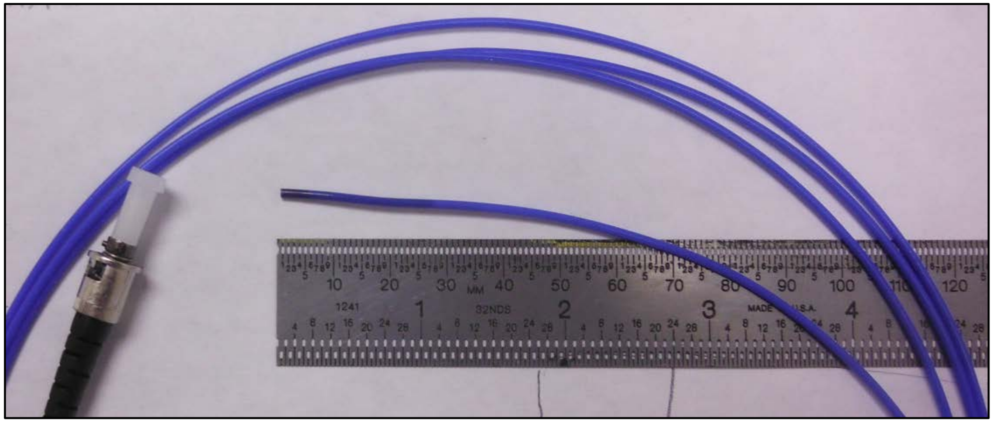

Experimental data of temporary wound cavity maximum diameter for 2-gr and 64-gr FSPs penetrating different simulants for human tissue – dynamic response is again similar for all simulants – data is extracted from digital high speed video data

# Pressure Sensor Specifications

- Two (2) styles of sensors were deployed to measure dynamic pressure in the soft tissue simulant during ballistic penetration.
- **PCB 138A06 tourmaline underwater blast pressure sensor**
  - 5000 psi range
  - 9.6-mm diameter
  - 666 kHz bandwidth
- **FISO FOP-M-PK fiber optic pressure sensor (Fabry-Perot)**
  - 1000 psi range
  - 1.7-mm diameter
  - 200 kHz or 7,340 psi/ms bandwidth.



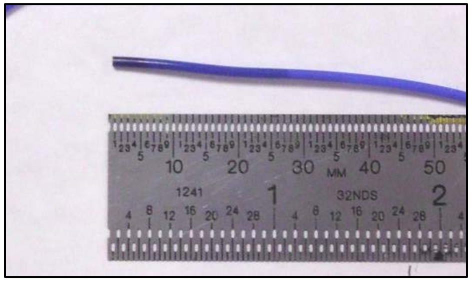
**PCB 138A06 tourmaline underwater blast pressure sensor**



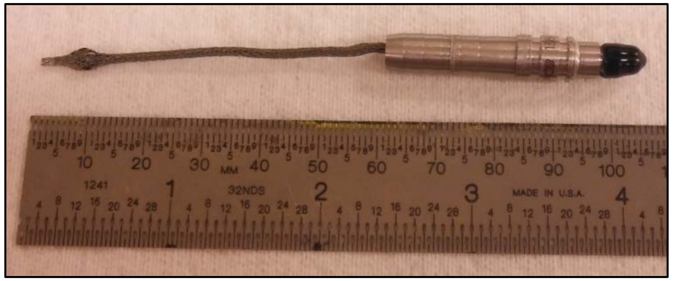
**FISO FOP-M-PK fiber optic pressure sensor**

# New Sensor Array

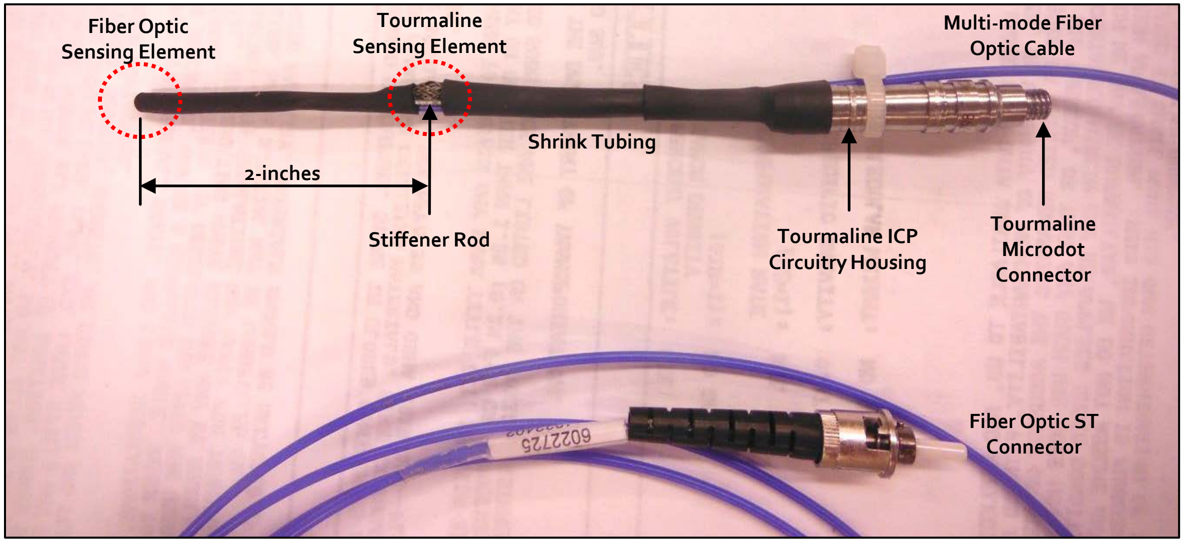
- The fiber optic and tourmaline pressure sensors were repackaged into a custom sensor array to facilitate more accurate and precise placement in the gelatin and to improve the quality of data return
- The silicone oil filled tube was removed from tourmaline pressure sensor assembly
  - Preliminary studies showed that the oil filled tube was preventing high frequency shock fronts from being resolved by the sensor
  - Eliminating the tube greatly reduces overall foot print of the sensor
- The fiber optic sensing element was positioned 2-inches in front of the tourmaline sensing element on the array
- The linear orientation of the two sensors was maintained via a metal stiffener rod that ran along the axis of the sensor array
  - The stiffener also limited the motion of the tourmaline element and sensor wires during the penetration event, acceleration of the sensing element and rubbing of the sensor wires can introduce significant noise and erroneous pressure data
- The components of the sensor array were secured into a single robust package using shrink tubing



Fiber optic sensor head



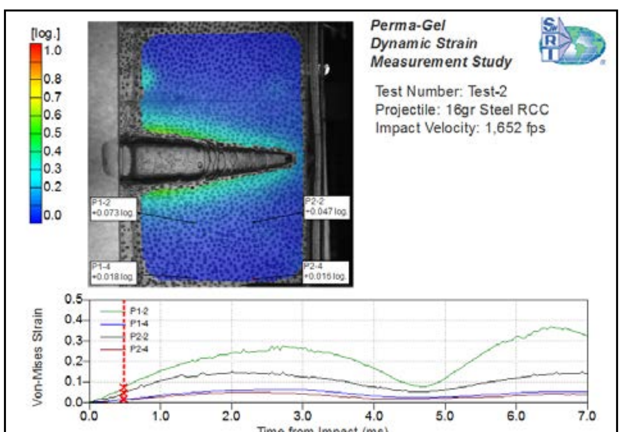
Tourmaline sensor without oil filled tube.



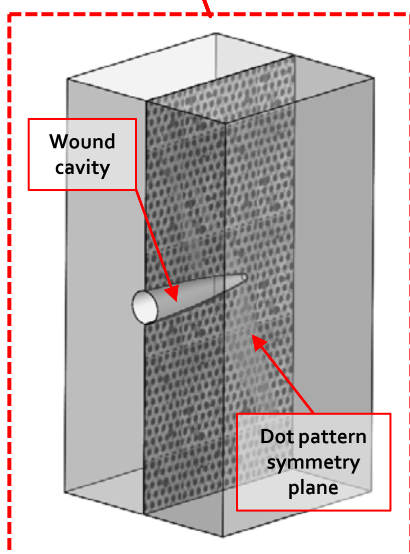

Sensor array package

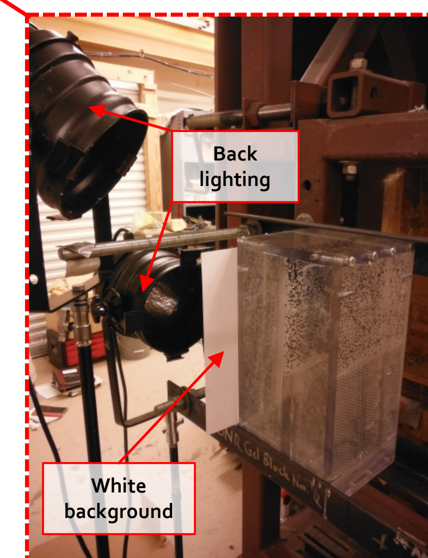
# Displacement and Strain Measurements Digital Image Correlation Method

- **A Digital Image Correlation (DIC) technique was implemented to measure dynamic displacements and strain along a cross-section plane intersecting the wound cavity.**
- **Stereo camera pair was used with 3-D DIC analysis to account for any out-of-plane deformation of the cross-section plane.**
  - Two (2) Phantom v711 high speed cameras
  - 13.1 degree relative angle
  - ARAMIS software used for DIC calibration and analysis
- **Measurement Capabilities**
  - Radial, axial, and out-of-plane displacement and deformation
  - Radial and axial strain
  - Shear strain
  - Von-Mises (max. distortion) and Tresca (max. shear) failure strain formulations
- **Back-lighting was used to create silhouette of projectile and dot pattern.**
  - Maximize contrast between black dots and white background.

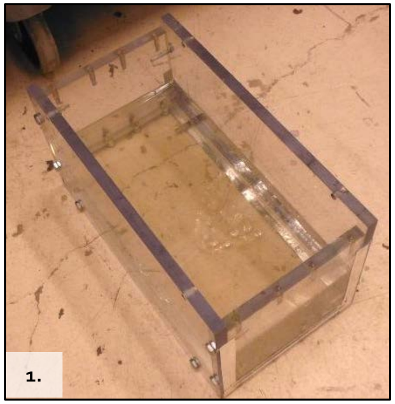






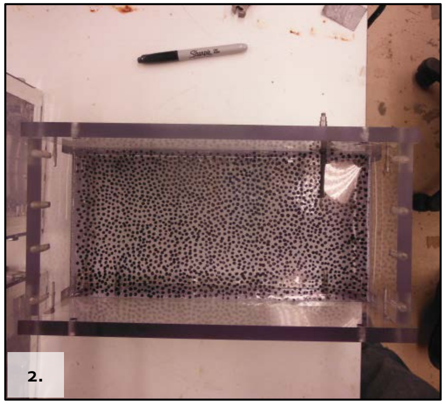



# Embedding Dot Pattern and Pressure Sensor



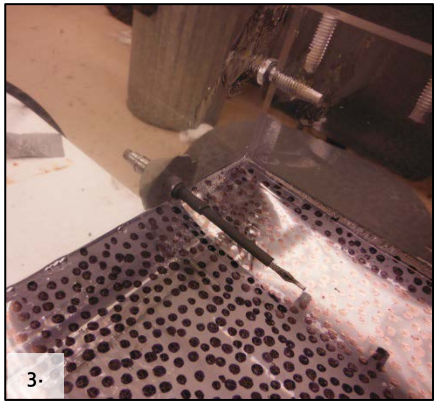
1.

A transparent polycarbonate mold was filled half way with molten Perma-Gel. The mold was placed in an oven for approximately 8 hours at 235$^{\circ}$F to allow the gelatin to de-gas. After all bubbles had been evacuated, the molten gelatin was allowed to solidify at room temperature.



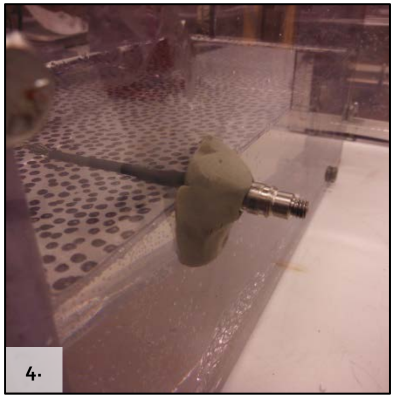
2.

Once solidified, a random dot pattern was applied to the surface of the gelatin using a Sharpie brand permanent marker. The dots were approximately 4-mm in diameter and were spaced approximately 4-mm center to center.



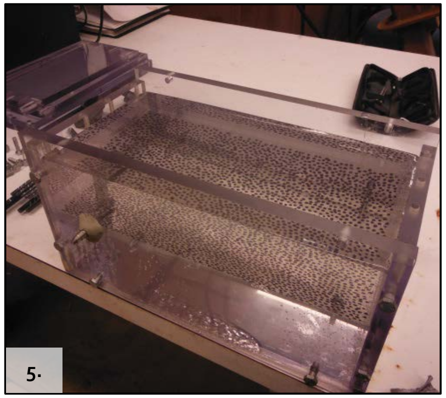
3.

A pressure sensor was cast in the gelatin on the dot plane. It was held in place during casting via a clearance hole located in the back panel of the mold. The pressure sensor was positioned 2-inches from the back face of the gelatin and 2-inches from the base or top, depending on the orientation of the block in the fixture.



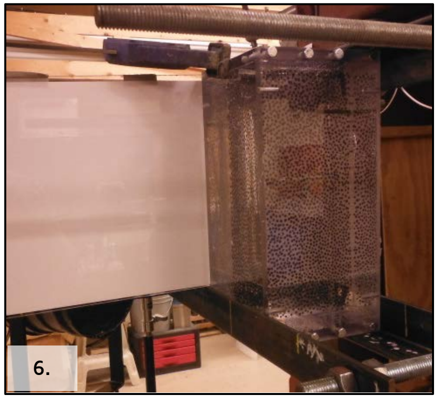
4.

The interface between the clearance hole and pressure sensor was sealed using clay.



5.

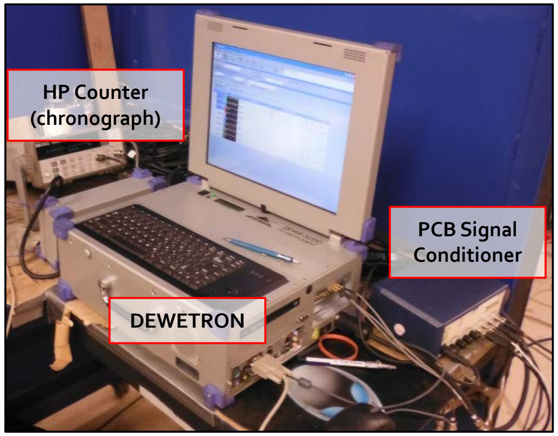
A layer of molten gelatin was then poured on top of the dot pattern, filling the mold to about 1-inch from the top. A heat gun was used to de-gas the molten gelatin as much as possible before it was allowed to solidify at room temperature.



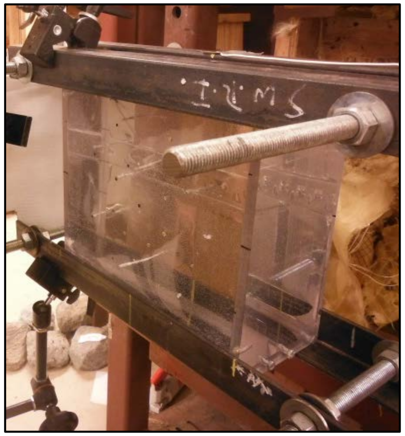
6.

Once solidified, the side panel was bolted to the mold and the back panel holding the pressure sensor was removed. The mold was then rolled 90 degrees so that its back face was facing up. The remaining 1-inch air gap was filled with molten gelatin and allowed to solidify at room temperature. After the gelatin solidified, the front panel covering the strike face was removed.

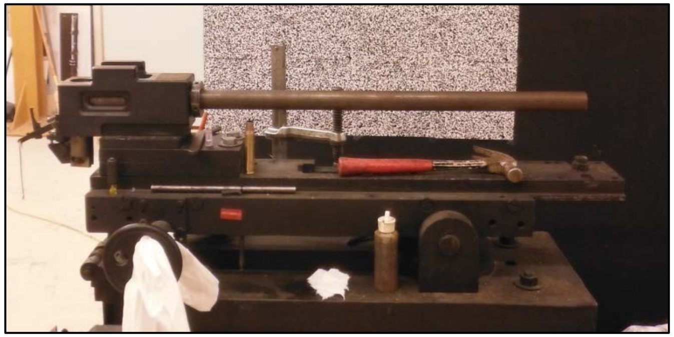
# Range Configuration

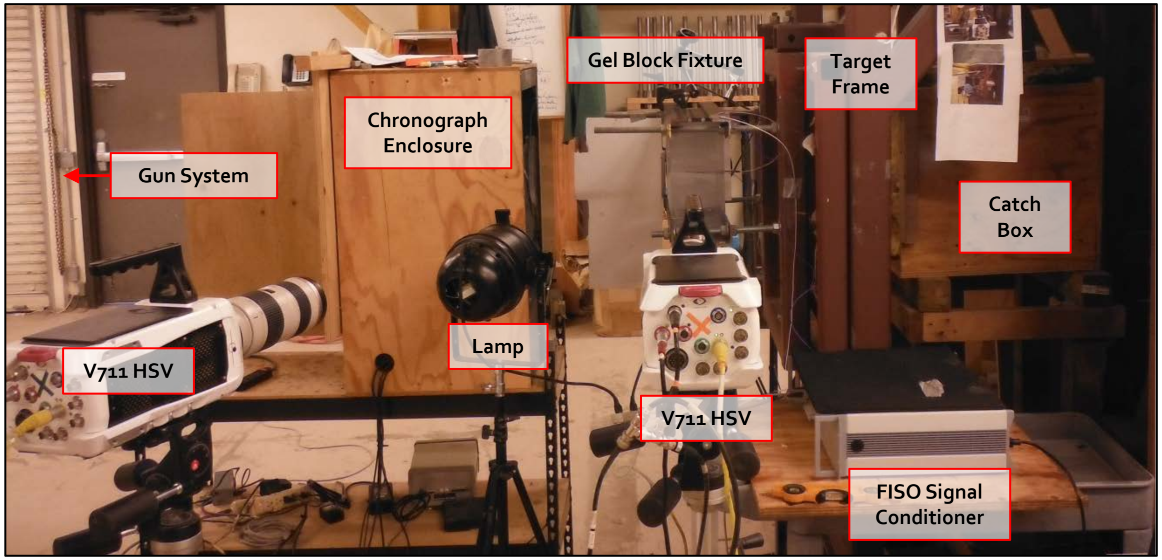


Data Acquisition Station


Gelatin Block Fixture


Gelatin Back Lighting

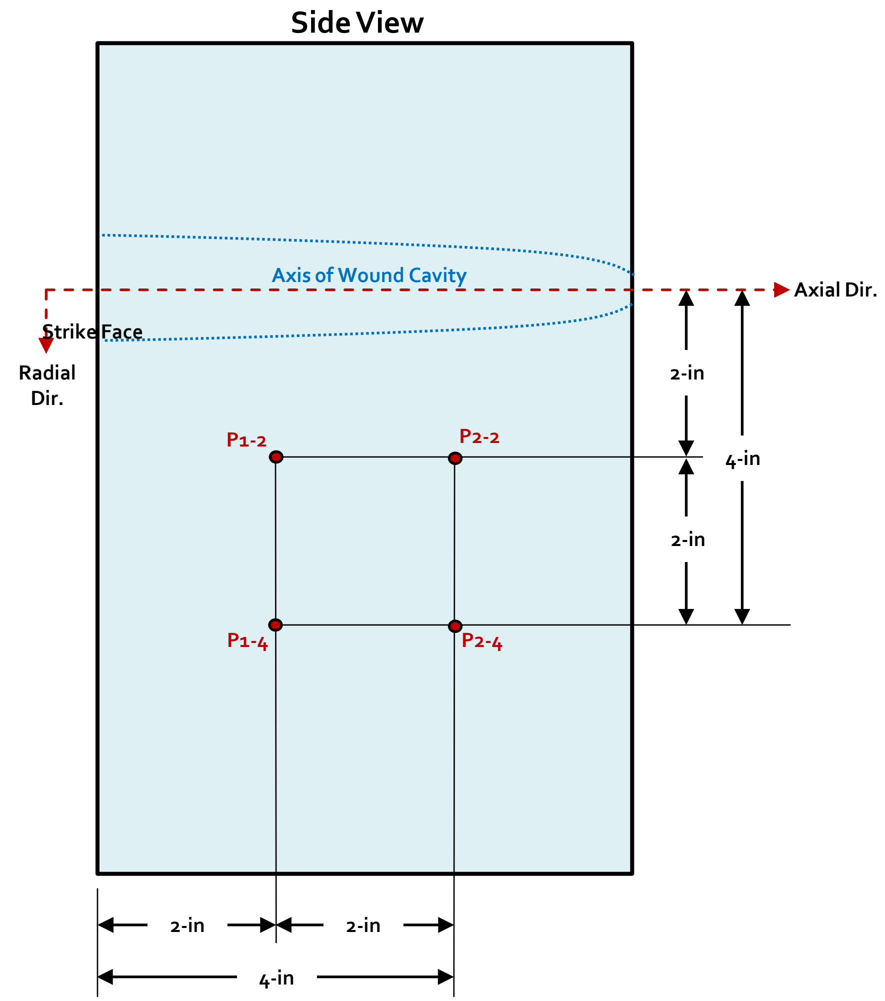

Universal Gun System (0.50 BMG shown)



Range Configuration

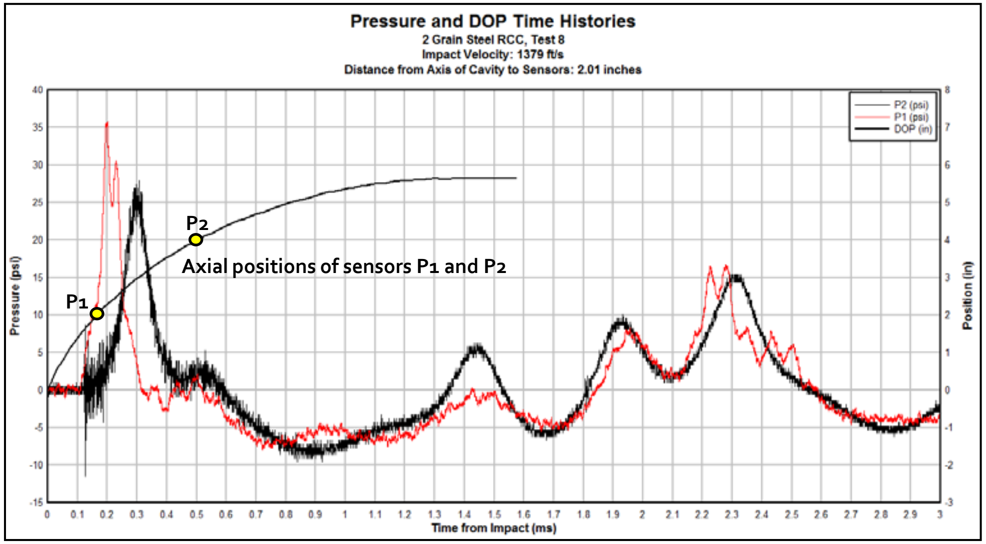
# Pressure Measurement Locations

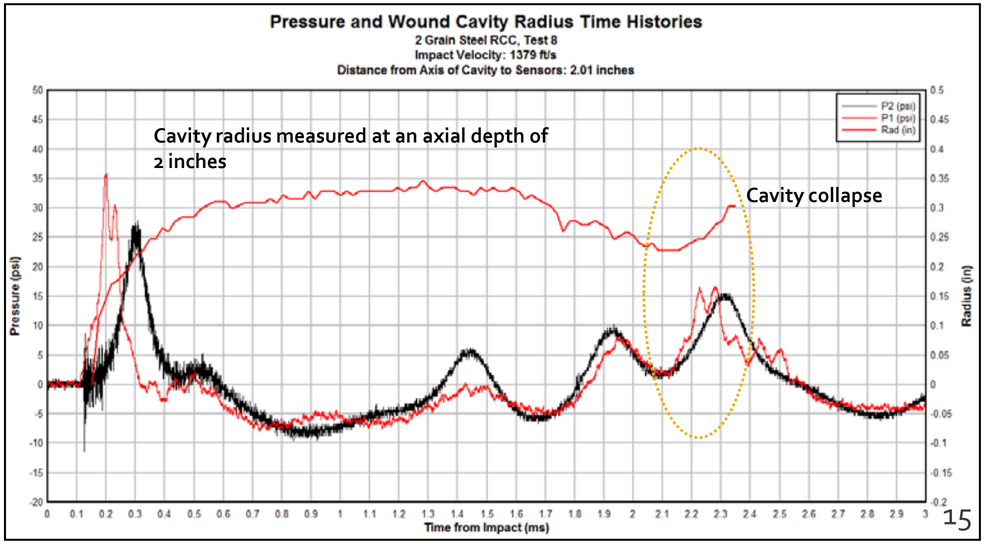
- For each nominal velocity, dynamic pressure data was collected at four (4) different locations with respect to the axis of the wound cavity.
  - Two (2) depths along the axial direction
  - Two (2) distances along the radial direction
  - Four (4) total locations for each nominal velocity
- The measurement locations for the pressure and strain results are referenced using the nomenclature shown in the figure to the right.



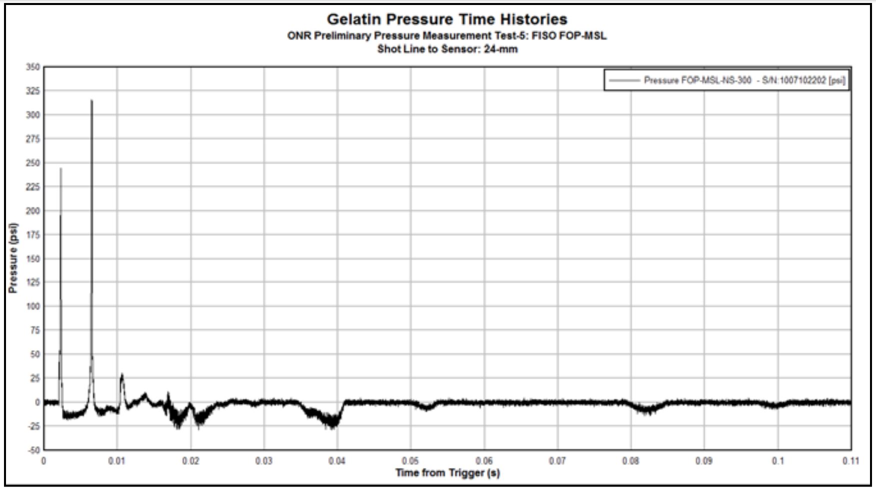
# Dynamic Pressure Response Example – 2 gr RCC

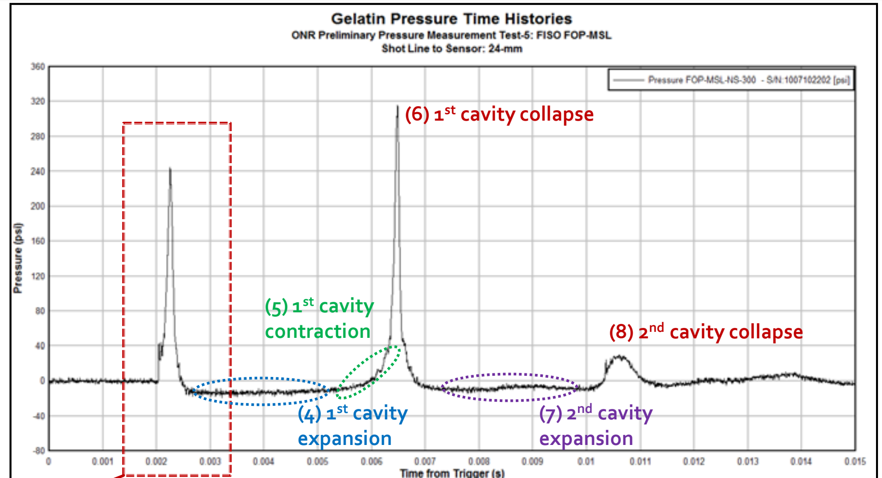
- Projectile depth of penetration (DOP) and wound cavity radius time histories are plotted with the pressure time histories from locations P1-2 and P2-2.
  - Time zero is the moment the projectile impacted the front face of the gelatin.
  - The DOP was measured from the front face of the projectile with respect to the front face of the gelatin.
  - The wound cavity radius was measured at a depth of 2 inches along the axial direction (P1-2 location).
- Positive pressure wave arrives at the sensor locations before projectile.
  - Compression wave in this case, no shock for this impact condition
- Positive pressure wave completely pass the sensors before maximum wound cavity radius is reached.
  - The gelatin is in a state of negative pressure when the wound cavity reaches its maximum radius – cavitation "vacuum" in wound cavity
  - Pressure begins to rise as the cavity begins to contract.
  - The collapse of the cavity generates another positive pressure wave(s).



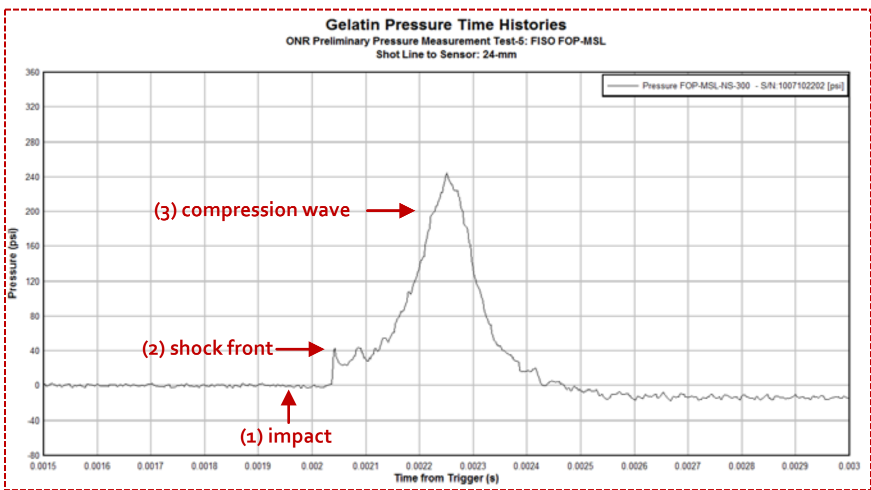



# Dynamic Pressure Response Example – 0.22 LR solid

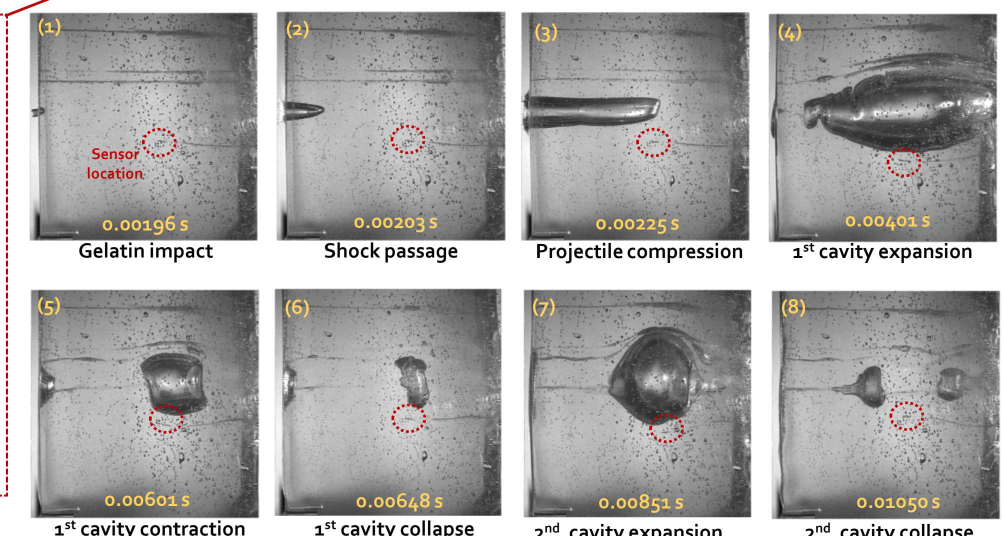


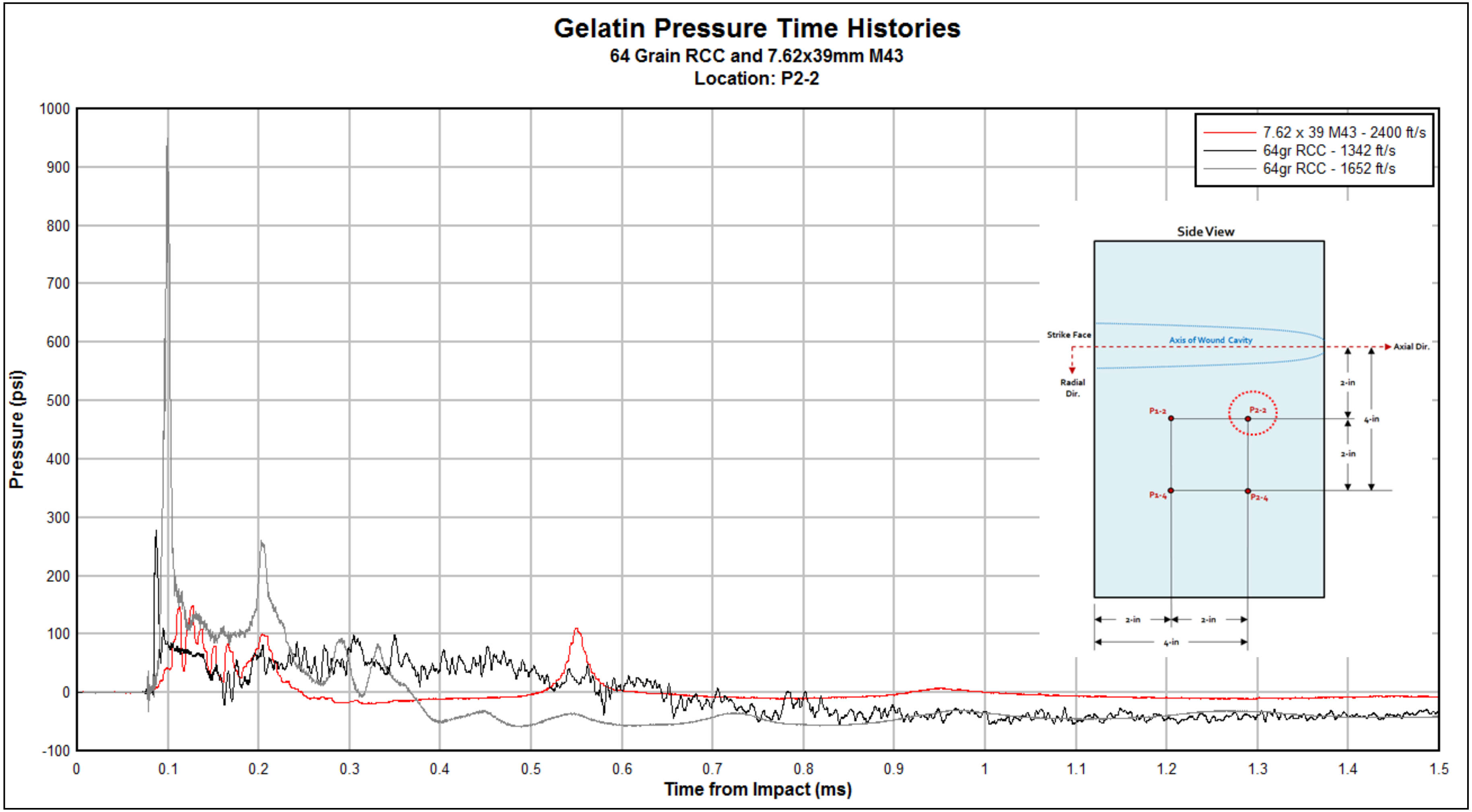

Time domain covering all pressure transients during the penetration event.




Initial passage of shock front (2) followed by compression (3) from projectile passage.

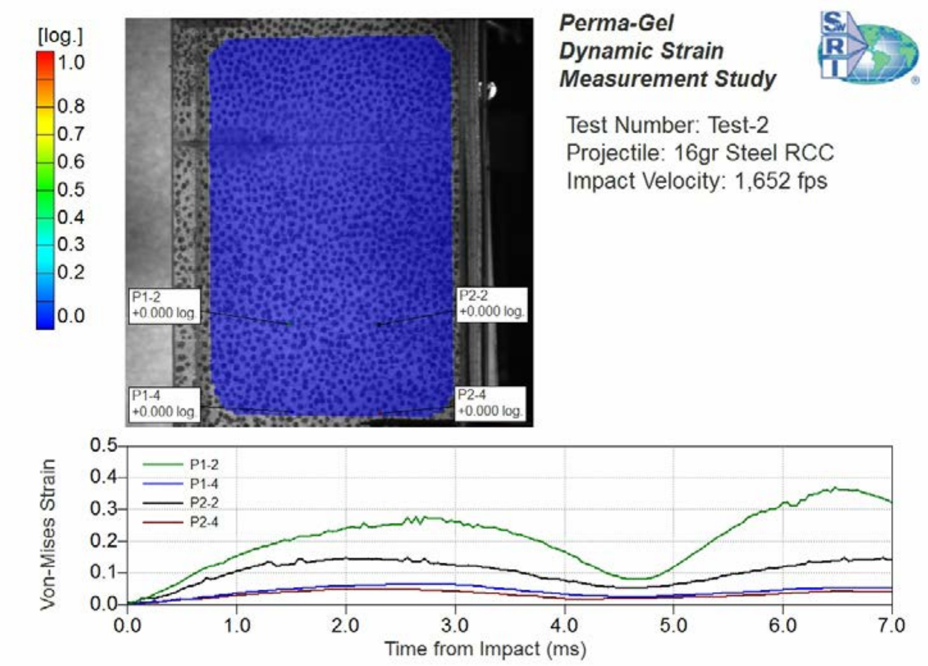


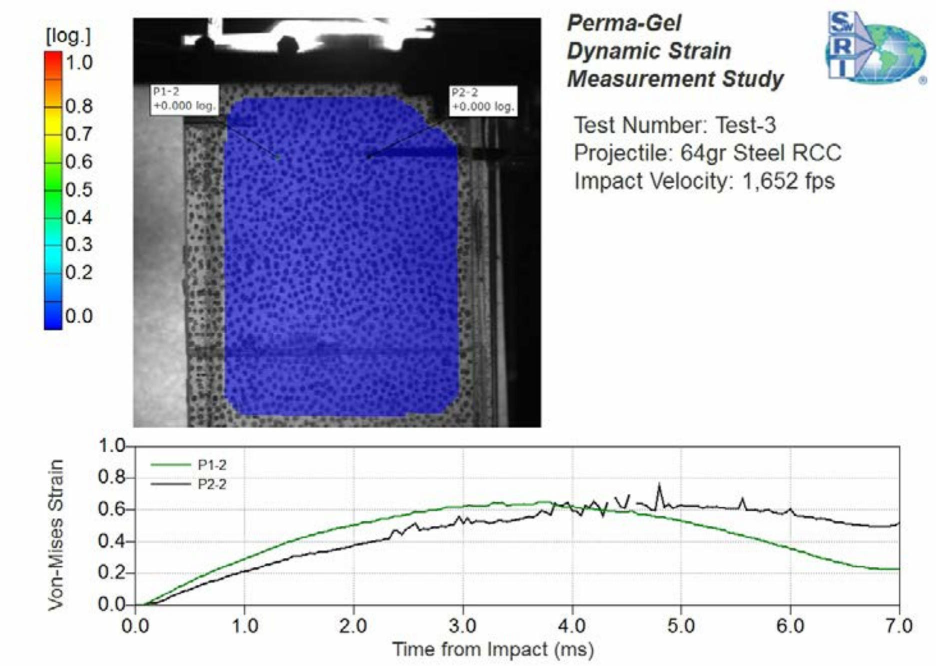
# Comparison of Pressure Response – 64 gr RCC and 7.62 x 39 (PS)



# 16gr & 64gr RCC Strain Response

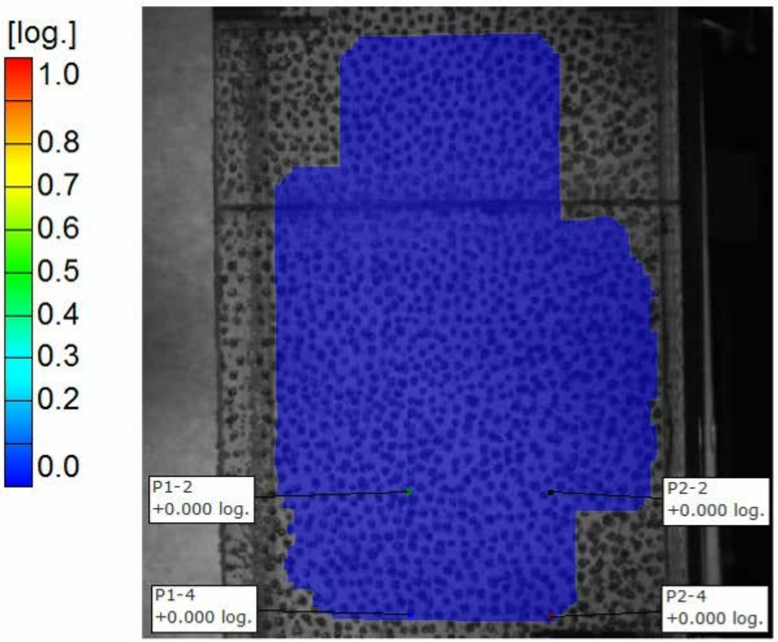
## ARAMIS Summary



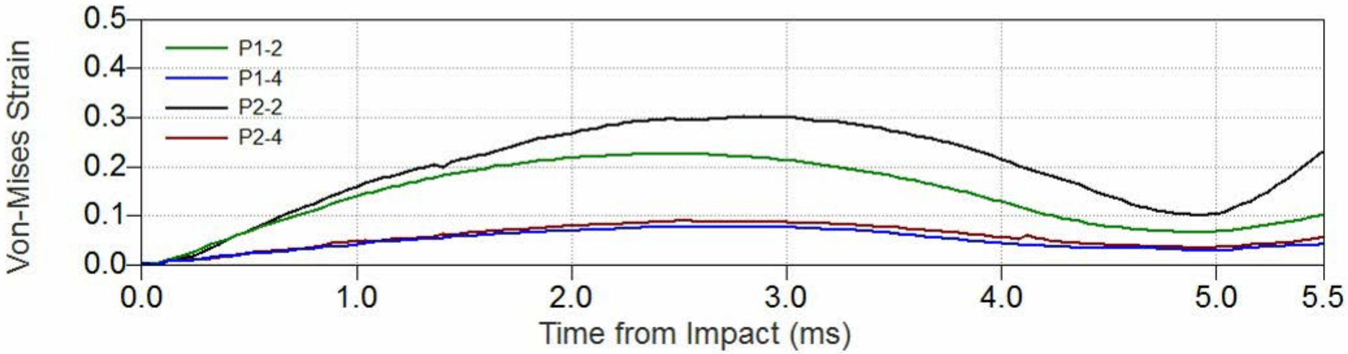
# 7.62 x 39 PS Strain Response

## ARAMIS Summary

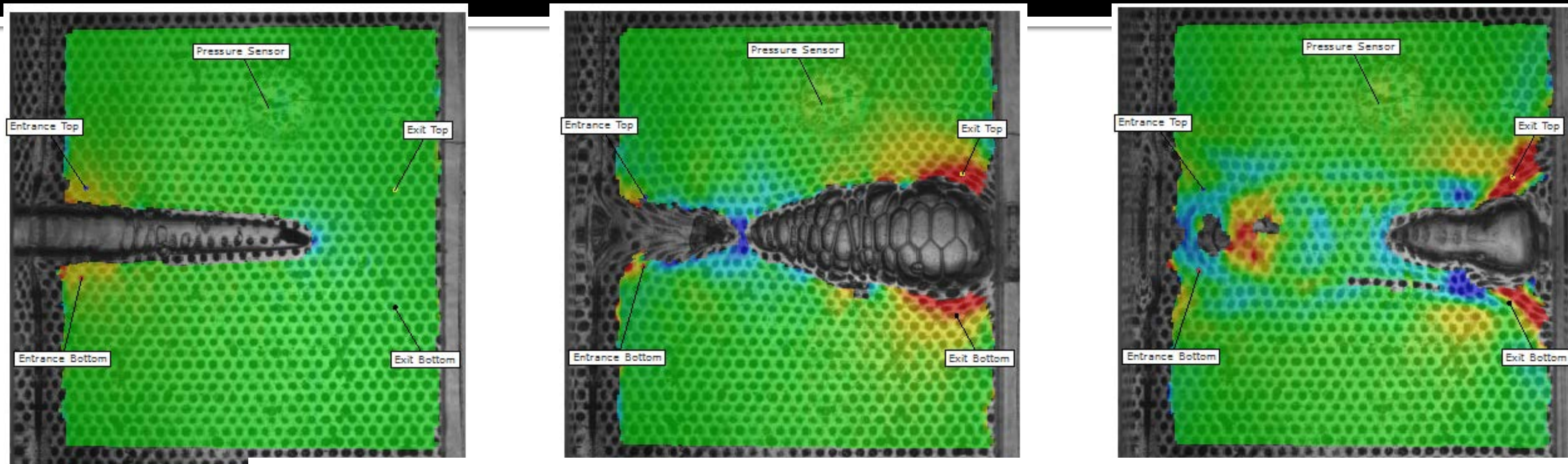



***Perma-Gel Dynamic Strain Measurement Study***

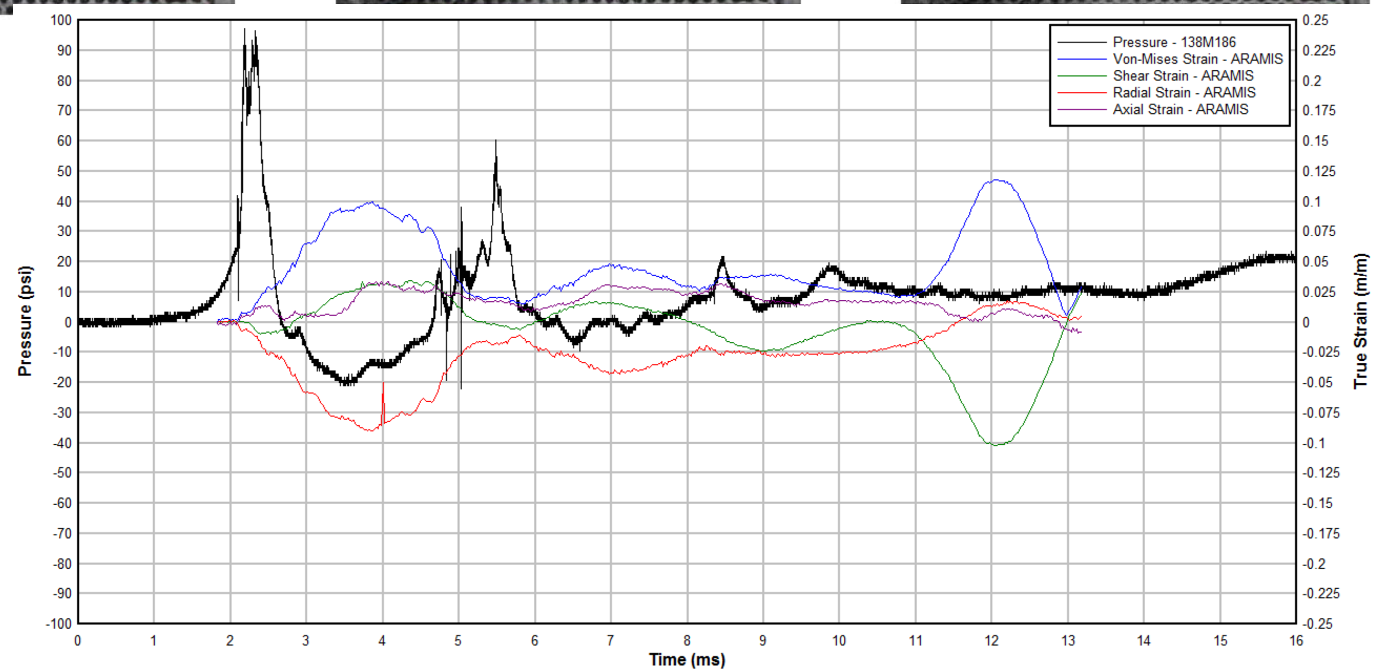
Test Number: Test-2
Projectile: 7.62 x 39 PS
Impact Velocity: 2,377 fps



# Aramis Strain Field Data
# 0.22-cal LR impacting at 1,045 ft/s

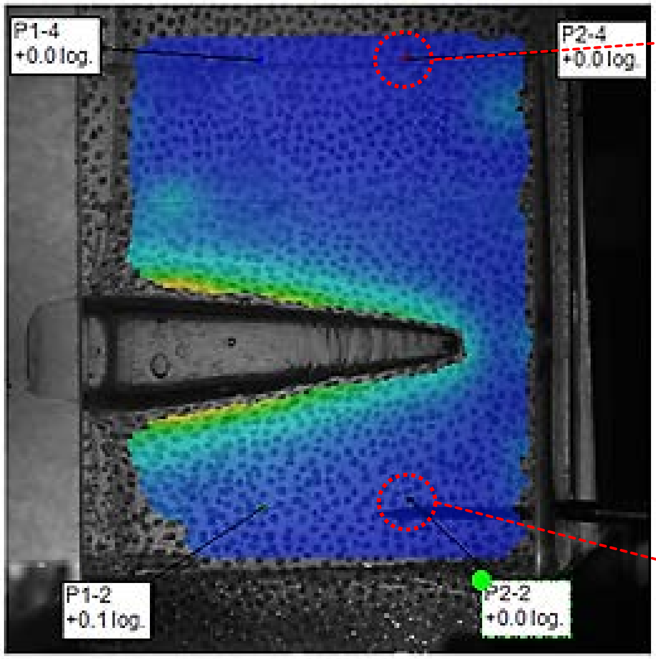


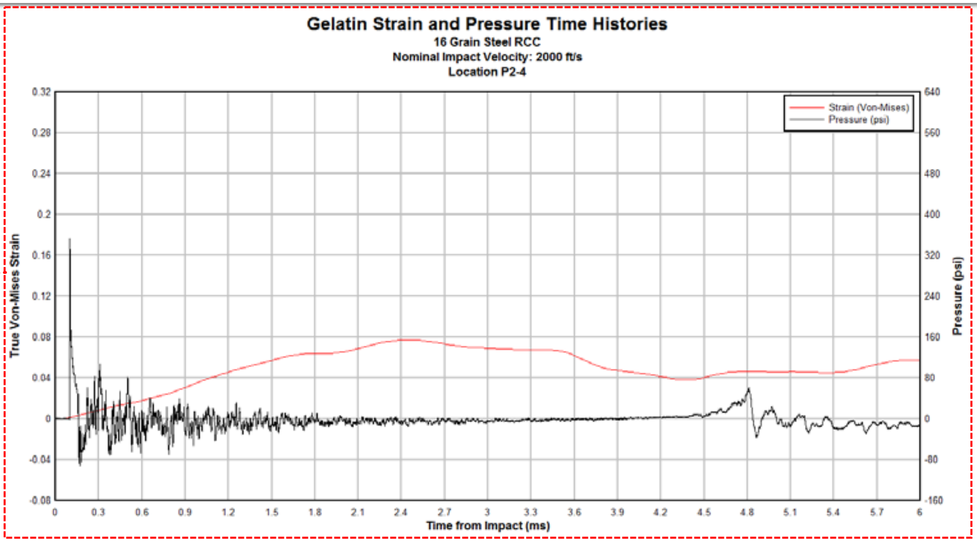

Pressure and strain data (at 3.5" from strike face and 1.9" above shot centerline)

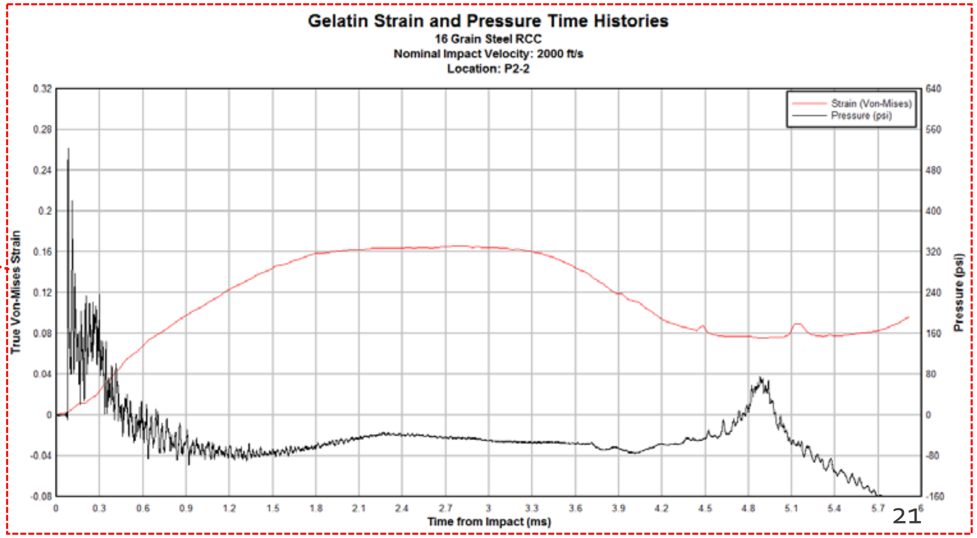


# 16gr RCC Strain and Pressure
## Impact Velocity: 2000 ft/s

**Strain and Pressure Measurement Locations**



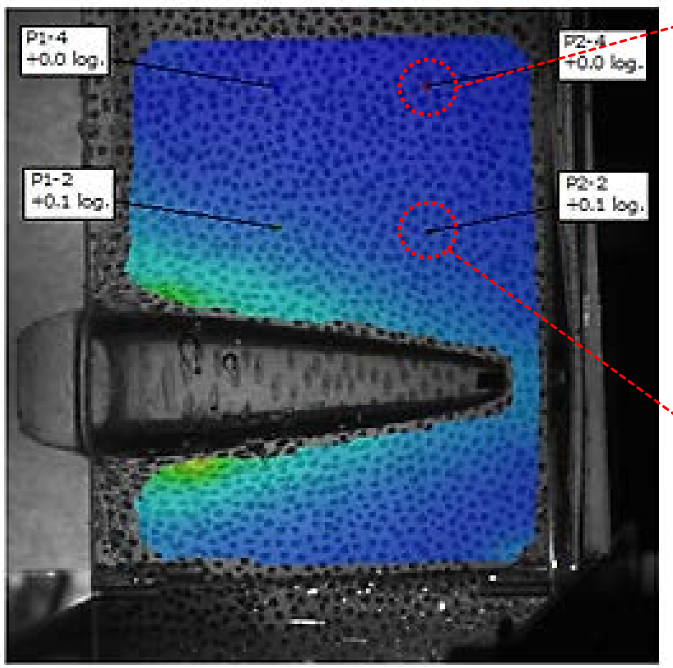



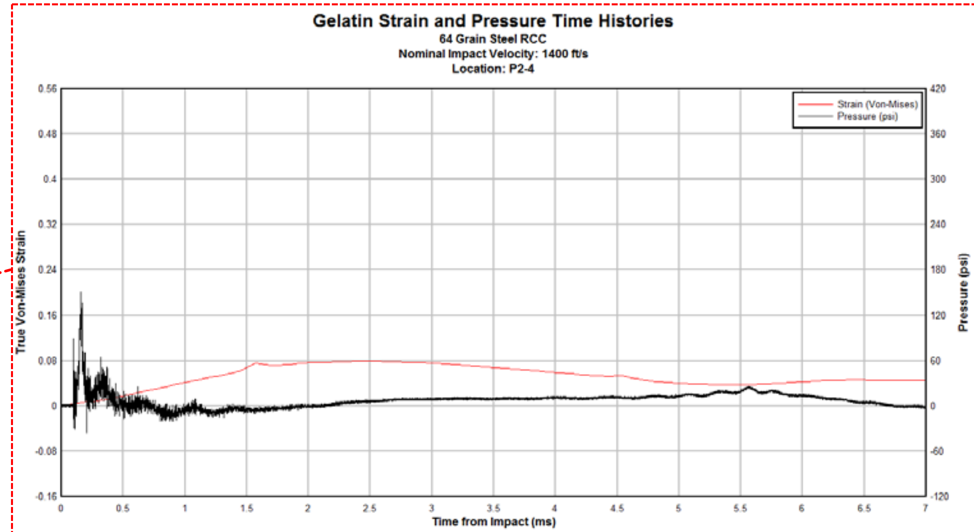



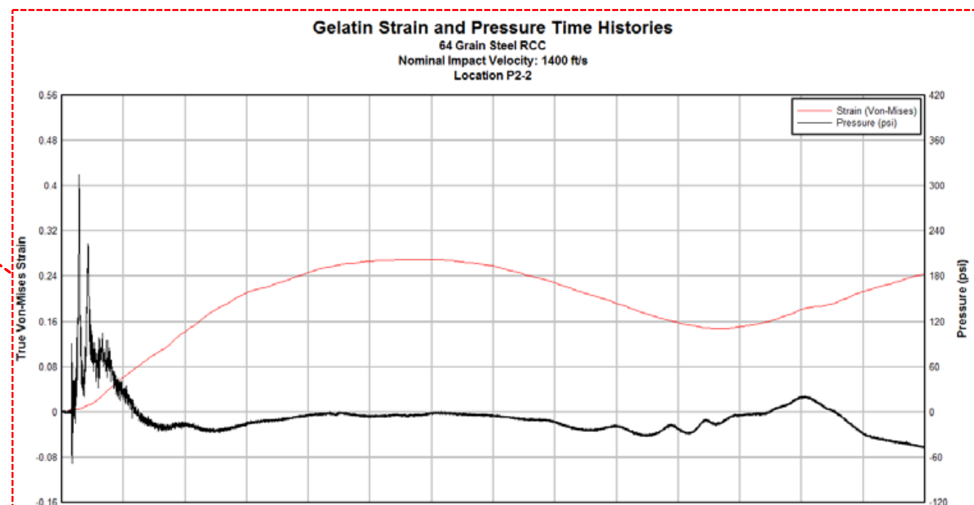
# 64gr RCC Strain and Pressure

## Impact Velocity: 1400 ft/s

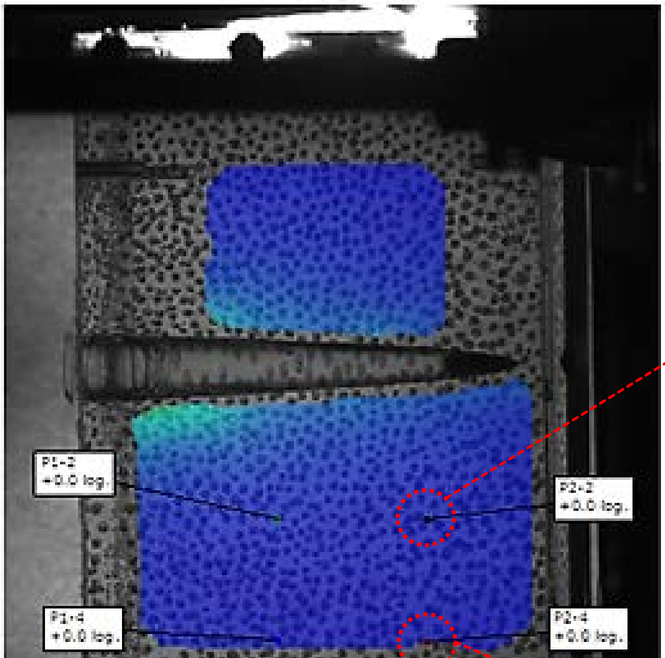
### Strain and Pressure Measurement Locations



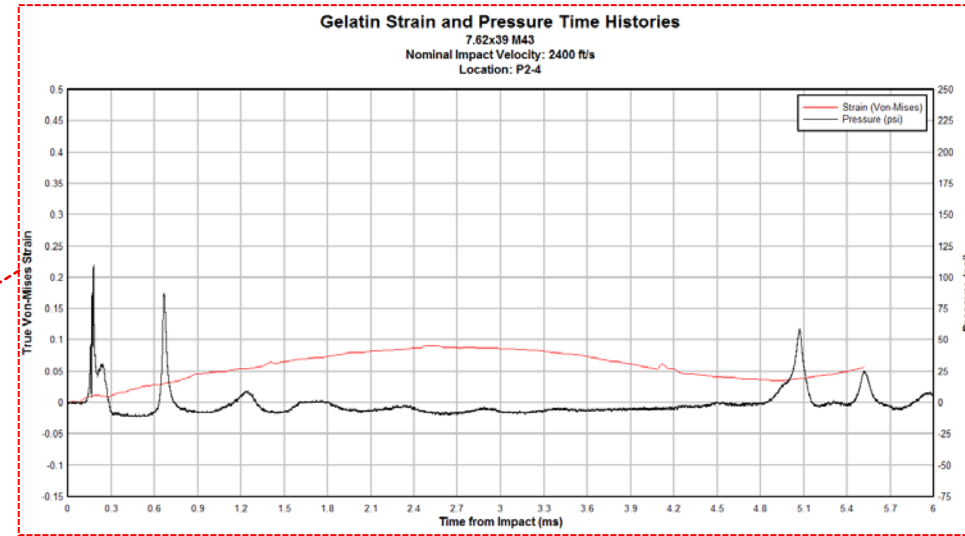



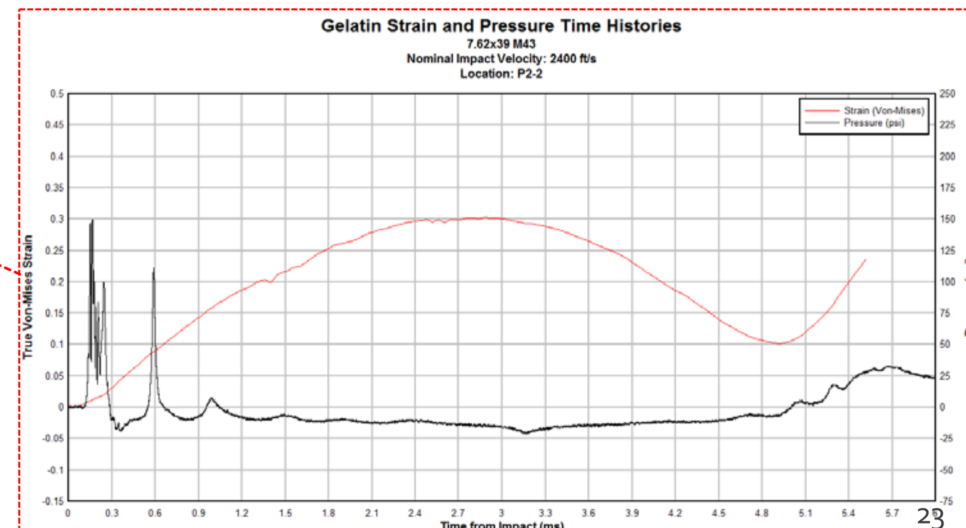



# 7.62 x 39 (PS) Strain and Pressure
## Impact Velocity: 2400 ft/s

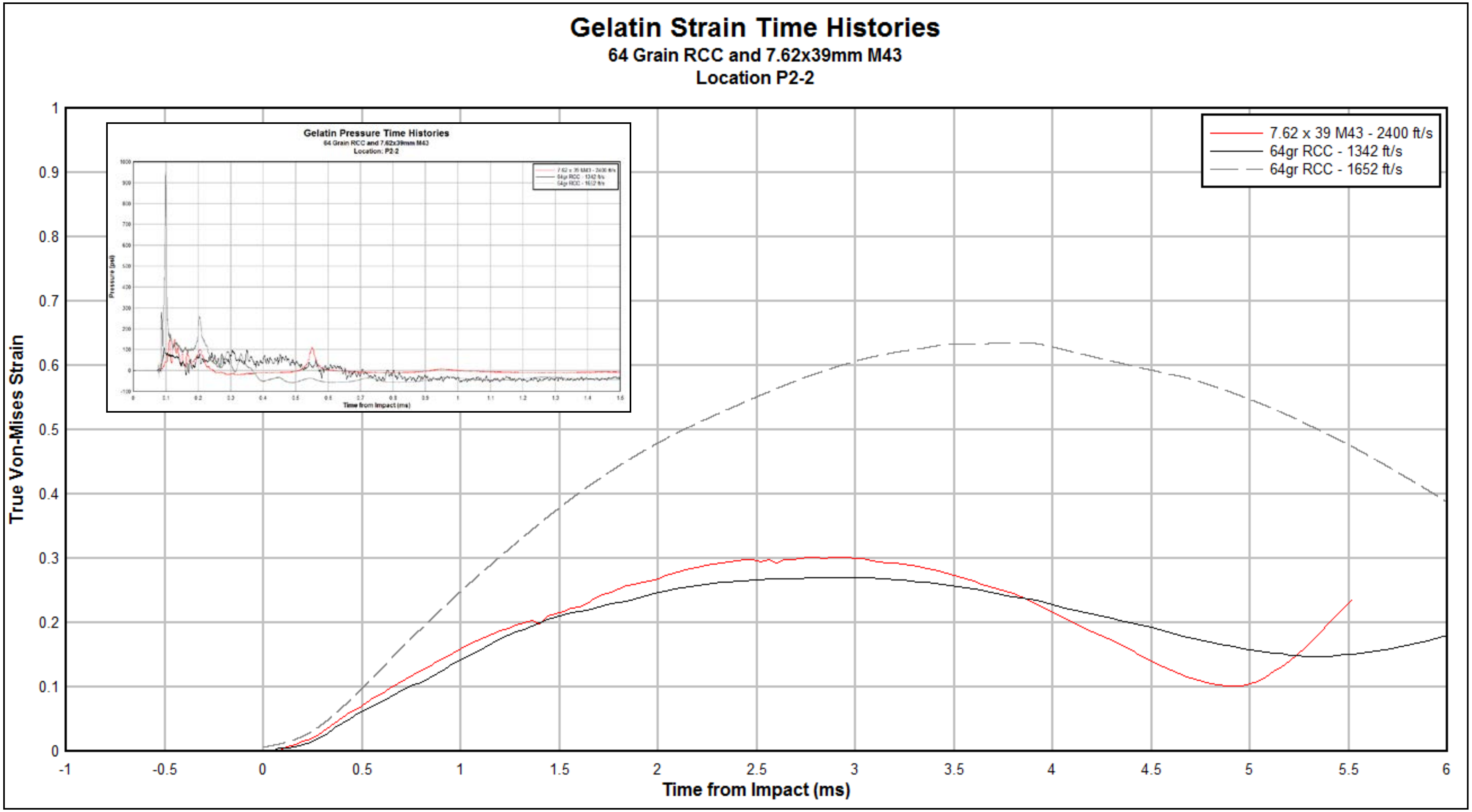



Strain and Pressure Measurement Locations



# 64gr RCC and 7.62 x 39 (PS) Projectiles – Strain Histories



# Summary and Conclusions

- An experimental methodology was developed to measure pressure and strain due to penetrating injuries from ballistic impact
- Dynamic pressure and strain time histories were successfully measured, providing peak values at critical points in the dynamic event (initial impact, maximum cavity expansion, and cavity collapse)
- The data shows the complex dynamic interactions between the projectile and soft tissue during ballistic penetration
- This data can directly support simulation validation